AD-A285 423

AR-006-657

DSTO-TR-0006

DSTO

Design of Thermocouple Probes for Measurement of Rocket Exhaust Plume Temperatures

R.C. Warren

40pg

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Design of Thermocouple Probes for Measurement of Rocket Exhaust Plume Temperatures

R.C. Warren

Aeronautical and Maritime Research Laboratory

ABSTRACT

Technical Report

This paper summarises a literature survey on high temperature measurement and describes the design of probes used in plume measurements. There were no cases reported of measurements in extreme environments such as exist in solid rocket exhausts, but there were a number of thermocouple designs which had been used under less extreme conditions and which could be further developed.

Tungsten-rhenium(W-Rh) thermocouples had the combined properties of strength at high temperatures, high thermoelectric emf, and resistance to chemical attack. A shielded probe was required, both to protect the thermocouple junction, and to minimise radiative heat losses. After some experimentation, a twin shielded design made from molybdenum gave acceptable results. Corrections for thermal conduction losses were made based on a method obtained from the literature. Radiation losses were minimised with this probe design, and corrections for these losses were too complex and unreliable to be included.

Approved for public release

DSTO-TR-0006

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Published by

Aeronautical and Maritime Research Laboratory
GPO Box 4331
Melbourne Victoria 3001

Telephone: (03) 626 8111
Fax: (03) 626 8999

AR No. 008-651
May 1994

APPROVED FOR PUBLIC RELEASE

Design of Thermocouple Probes for Measurement of Rocket Exhaust Plume Temperatures

EXECUTIVE SUMMARY

There is considerable difficulty and expense involved in the measurement of the infra-red signature of rocket and aircraft exhaust plumes under in-service conditions, and it is often impossible to measure the plumes of enemy planes or missiles. The alternative is to calculate the appropriate emissions using sophisticated computer codes. Measurement of temperature profiles of rocket exhausts offers an important method for validating these codes.

Temperature profiles can be measured using non-intrusive methods, but these are complex and expensive. Intrusive probes based on thermocouples are a possible alternative, but a rocket exhaust presents a very extreme environment of high temperature, high velocity, high turbulence and chemical reactivity. These factors place severe constraints on the type and design of probe that can be used.

This paper summarises a literature survey on high temperature measurement and describes the design of probes used in plume measurements. There were no cases reported of measurements in extreme environments such as exist in solid rocket exhausts, but there were a number of thermocouple designs which had been used under less extreme conditions and which could be further developed. The literature survey also covered discussions of corrections for conduction and radiation losses.

Tungsten-rhenium(W-Rh) thermocouples were chosen because they had the combined properties of strength at high temperatures, high thermoelectric emf, and resistance to chemical attack. A shielded probe was used, both to protect the thermocouple junction, and to minimise radiative heat losses. After some experimentation, a twin shielded design made from molybdenum gave acceptable results. Corrections for thermal conduction losses were made based on a method obtained from the literature. Radiation losses were minimised with this probe design, and corrections for these losses were too complex and unreliable to be included.

Author

R.C. Warren
Explosives Ordnance Division

Bob Warren graduated with an MSc in Physics from the University of NSW in 1968. Before joining DSTO in 1972 he worked in the fields of X-ray crystallography, neutron diffraction from titanium alloys and X-ray fluorescence spectroscopy of paints. At DSTO Salisbury he studied the mechanical properties of composite and nitrocellulose based propellants, and made significant contributions to the understanding of molecular relaxations in nitrocellulose. After a 2 year attachment in the UK he studied the rheology of nitrocellulose propellants. He is now working in Explosives Ordnance Division, Salisbury on the prediction of rocket exhaust plumes.

Contents

1. Introduction

It is very difficult and expensive to measure the IR signature of rocket and aircraft exhaust plumes under service conditions, and it is often impossible to measure the plumes of enemy planes or missiles. The alternative is to calculate the appropriate emissions using sophisticated computer codes. A number of computer codes are available for the calculation of rocket exhaust plumes. These computer codes have not been fully validated, and validation of the codes is required to increase confidence in their use and to provide data for their improvement. Measurement of temperature profiles of rocket exhausts offers an important method for validating codes.

Temperature profiles can be measured using intrusive or non-intrusive methods. Non-intrusive optical methods based on CARS have been developed in the UK for temperature measurement of particulate free plumes, but the methods are complex and expensive. Intrusive probes based on thermocouples are a possible alternative, but a rocket exhaust presents a very extreme environment of high temperature, high velocity, high turbulence and chemical reactivity. These factors place severe constraints on the type and design of probe that can be used.

In the current work an intrusive probe was the only practical option. There were no standard thermocouple probes available for plume measurement, so it was necessary to develop probes in-house. A literature survey did not reveal any suitable designs, but much information was found on which to base a design. A twin shielded molybdenum probe containing a tugsten-rhenium thermocouple was designed and tested with a small scale motor. The testing of the probe and it use in measuring temperature in the plume of an air-air missile are discribed in a separate paper[1].

This paper summarises the literature survey on high temperature measurement and describes the design of probes used in plume measurements. Corrections for conduction losses are also discussed.

2. Literature Survey

2.1 Thermocouple recovery and correction factors

In order to assess the results of experiments on thermocouple behaviour, it is necessary to understand the concepts of recovery factor and correction factor. A consistent and clear discussion is given by Cambel and Jennings in [2], and a summary of their discussion is given below.

The deviation of the measured temperature from the true total (or stagnation) temperature can be represented by a correction factor K, given by

$$K = \frac{T_p - T_s}{T_o - T_s}$$

Where T_p is the temperature recorded by the probe which may exchange heat with the environment through radiation and/or conduction, T_s is the static stream temperature and T_o is the total temperature. If the calibration factor for a probe is known, as well as the heat capacity and velocity of the gas, then the total temperature can be calculated from a measurement of the probe temperature.

If it is assumed that the temperature sensor exchanges no heat with its surroundings, any deviations between the sensor temperature and the total temperature of the flowing material will be due to the flow behaviour in the boundary layer around the sensor. The flow impinging on the front of the surface of the sensor is brought to rest, and its temperature is the total, or stagnation, temperature, T_o, which is given by

$$T_o = T_s + V^2 / 2c_p$$

where c_p is the specific heat and V the velocity. However, the flow around the remainder of the sensor will have a progressively smaller change in velocity compared with the flow at the tip, and the local temperature will be closer to the stream temperature. The sensor as a whole will therefore record a temperature T_{aw}, which is between T_s and T_o because the flow energy is only partly recovered. T_{aw} is given by

$$T_{aw} = T_s + r.V^2 / 2c_p$$

Rearranging and eliminating $V^2 / 2c_p$ gives

$$r = \frac{T_{aw} - T_s}{T_o - T_s}$$

The factor r is known as the recovery factor.

If a thermometer is designed such that heat losses are negligible, then $K \approx r$ *and* $T_{aw} \approx T_P$. However, this is an approximation and K is not synonymous with r.

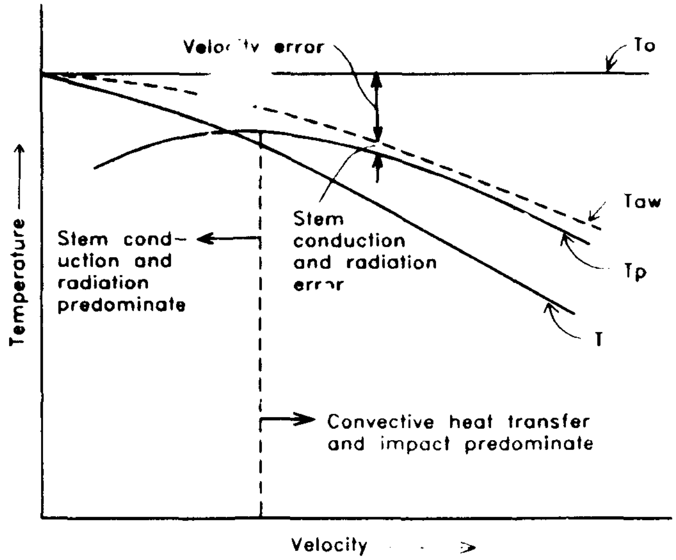


Figure 1: *Dependence of various temperatures on gas velocity from Cambel and Jennings[2].*

The difference between the two factors is illustrated in figure 1 from reference [2]. For flow with constant T_o, an increase in velocity decreases the static temperature, and the adiabatic sensor temperature T_{aw} decreases by a lesser amount. The temperature of the probe with heat losses, T_p, is lower than T_{aw}. At low velocities T_p, is much lower than T_{aw} because heat loss dominates the heat gain from convection.

As noted by Moffat [3], the performance of the most complex probe is determined by the junction inside it and the environment to which the junction is exposed. Radiation shields do not change the junction's response to its environment, they change the environment.

Moffat [3] reviewed the literature on the recovery factor of bare wire thermocouples and recommended values of

$r = 0.68 \pm 0.07$ wire normal to flow
$r = 0.86 \pm 0.09$ wire parallel to flow.

A spherical bead much larger than the wire diameter moves the value of r towards 0.75 for flow in both directions. Rough surfaced wires show higher recovery factors than smooth wires. Moffat[3] states that reproducibility of recovery factor seems to be about ±3% to 5% for junctions made with normal care by experienced technicians.

2.2 *Performance of various thermocouple types*

Thermocouples can be used in the bare wire state or in some type of shield to make a probe. An understanding of the behavior of bare wire thermocouples is important because these are the basis of shielded probes.

Bare wire thermocouples were studied in subsonic flows by Scadron and Warshawsky [4]. The thermocouples used are illustrated in figure 2 and the dimensions and materials are given in Table 1. Four pairs of thermocouple materials and three different wire diameters were used. The Mach number range was 0.1 to 0.9 and the Reynolds number based on wire diameter ranged between 250 and 30,000. The gas temperature was 573°K.

Detailed analyses were made assuming that bare wire thermocouples were mounted between supports with temperatures which did not vary significantly with time. Scadron and Warsawsky made a large number of measurements of time constants, and produced detailed calculations for evaluating time constants, conduction corrections and radiation corrections. However the subsonic corrections they derived are too complex for routine use.

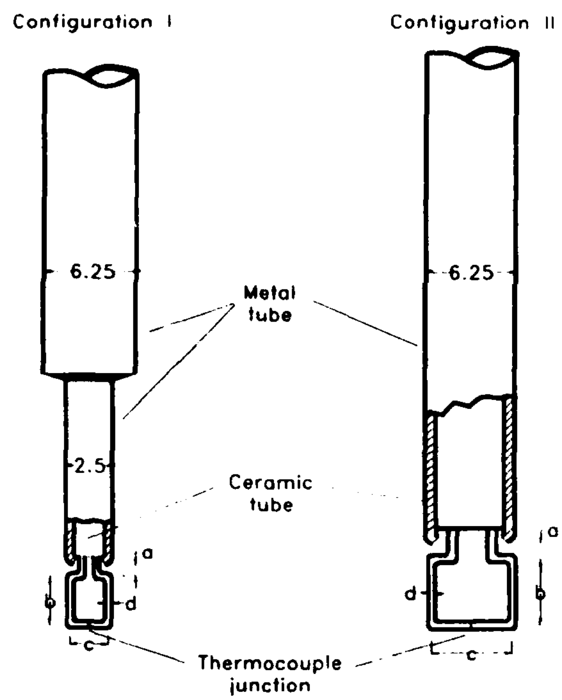


Figure 2: Probes from Scadron and Warshawsky [4].

Table 1:

Probe	Thermocouple material	Dimensions (mm) a	b	c	d	Configuration
A	Chromel-constantan	0.51	3.81	1.27	0.22	I
B	" "	1.02	7.62	2.54	0.45	I
C	" "	2.54	12.7	6.35	1.41	II
D	Iron-constantan	1.02	7.62	2.54	0.41	I
E	Chromel-alumel	1.02	7.62	2.54	0.39	I
F	Pt-13%Ro/Pt	1.02	7.62	2.54	0.44	I
G	Chromel-constantan	-	-	-	0.44	Straight wire

A summary of values of the ratio of measured temperature to total temperature, and static temperature to total temperature, versus Mach number is given in figure 3.

A major finding was that over the range of conditions studied, the Nusselt number for flow perpendicular to the wire was given by :-

$$Nu = (0.427 \pm 0.018).Re^{(0.515 \pm 0.005)}.Pr^{0.3}$$

or

$$Nu = (0.478 \pm 0.002).Re^{0.5}.Pr^{0.3}$$

where the variables used to calculate Re are evaluated at the total temperature.

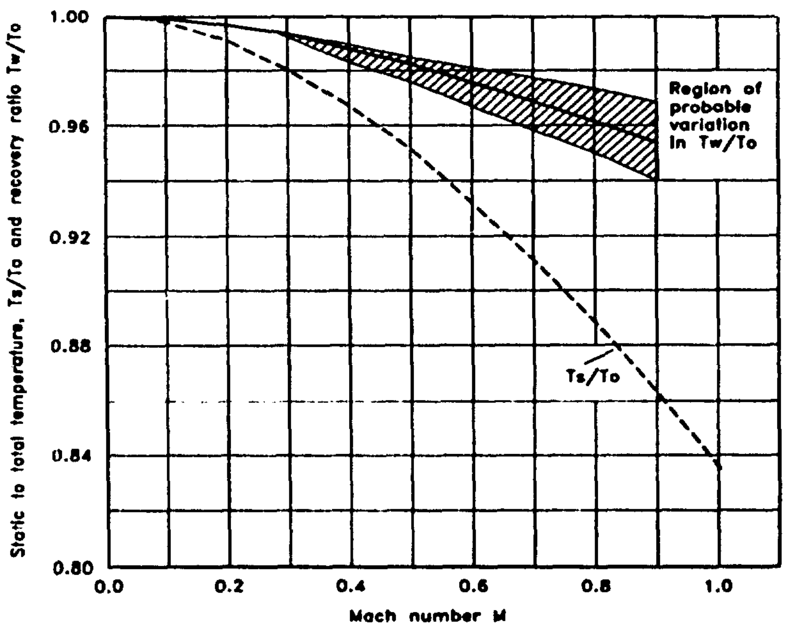


Figure 3: The ratio of measured temperature to total temperature, and static temperature to total temperature, versus Mach number from Scadron and Warshawsky [4].

Bare wire thermocouples, as well as shielded probes, were analysed by Stickney [5]. Six probes were tested, and they are illustrated in figure 4. The vent to entrance area ratio of the shielded probe 6 was 0.43. The vent in probe 5 consisted of 2 unused holes in the insulator for thermocouple lead wires which were not dimensioned. The wire diameter was 0.305 mm, and assuming that the hole was 0.4 mm in diameter, the area ratio would be 0.2. Probe 4 was only partially shielded, so a vent to entrance ratio is not relevant.

So called recovery factors (r), which are referred to as calibration factors (K) here, were measured over the Mach number range 0.2 to 2.2 at a total temperature of 21-38°C. At these temperatures heat flow from the probe would be negligible, and r can be equated to K and measured directly. The measured recovery factors are plotted in figure 5.

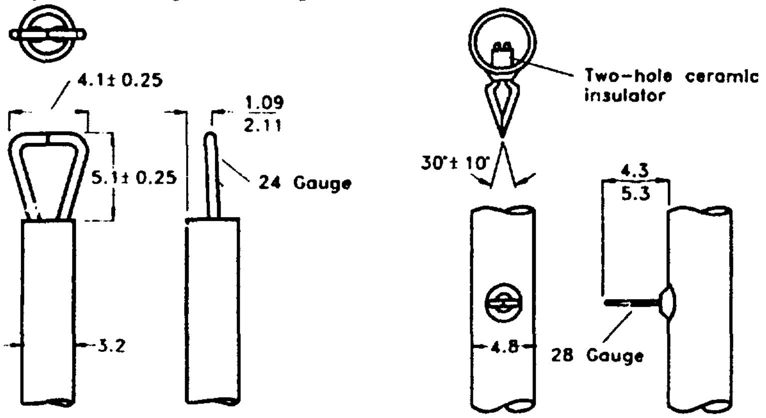


Figure 4(a): Probes 1 and 2 from Stickney [5].

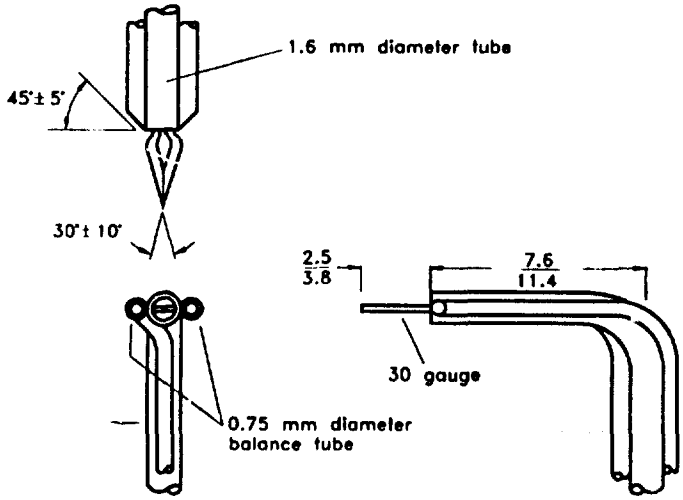


Figure 4(b): Probe 3 from Stickney [5].

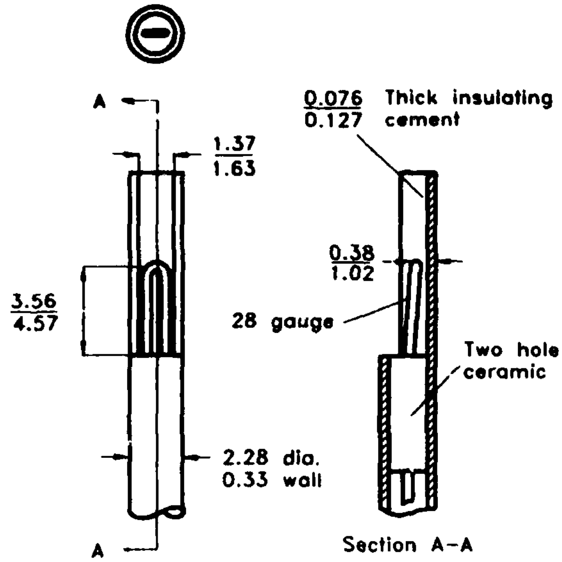


Figure 4(c): *Probe 4 from Stickney [5].*

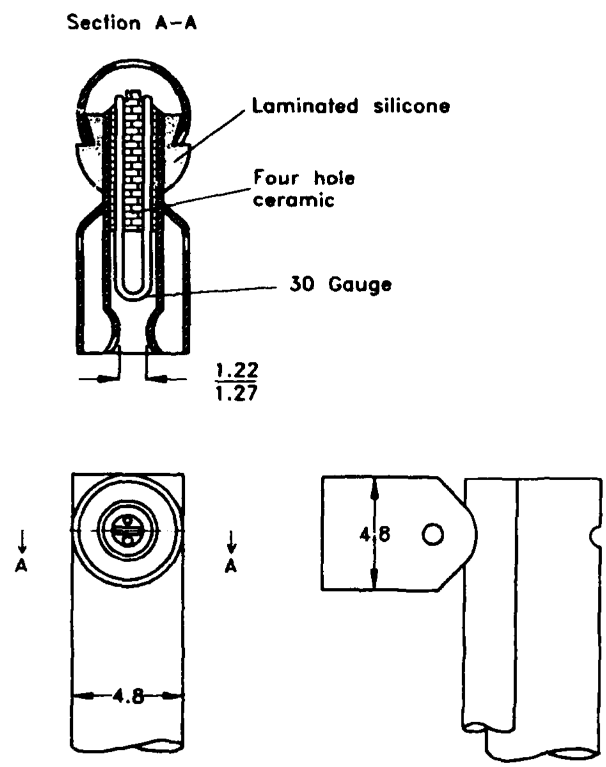


Figure 4(d): *Probe 5 from Stickney [5].*

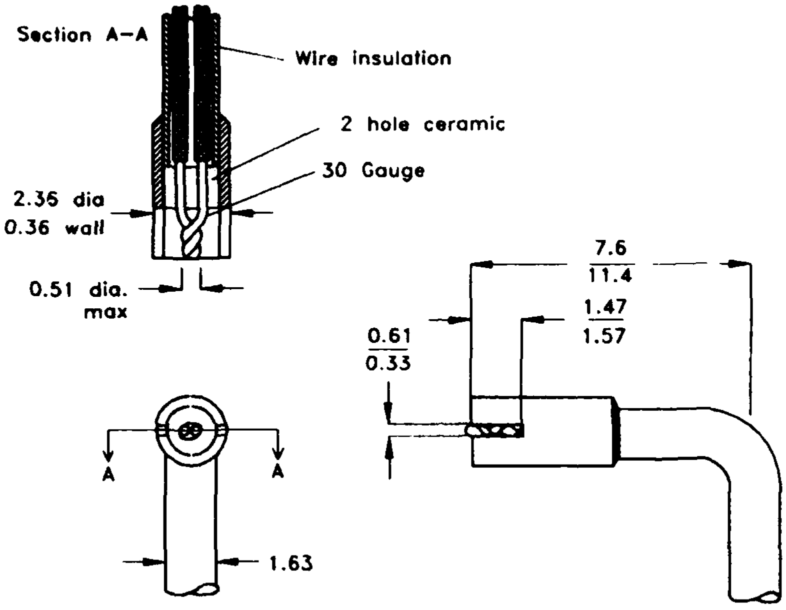


Figure 4(e): Probe 6 from Stickney [5].

From figure 5 it can be seen that the unshielded probes were strongly affected by the transition from subsonic to supersonic flow. Probe 2 shows that while the probe remains behind the bow shock the curve is a continuation of the subsonic curve, but when the sensor breaks through there is a sudden drop in recovery ratio. The sensors in the shielded probes always remain behind the bow shock. The shielded probes showed smaller variations of recovery factor with probe design, and the double shielded probe 5 showed the least effect of changing Mach number.

These results show that for flows involving both supersonic and subsonic regions shielded probes must be used.

A low temperature shielded probe for supersonic flows was developed by Goldstein and Scherrer [6]. A section through the probe is illustrated in figure 6. The main part of the probe was made from lucite, and the sensor was placed just above the hemispherical surface at the back of the probe because this was where the flow was nearly stagnant, but there was sufficient flow for heat transfer to the sensor.

The air sample enters the blunt shield at a subsonic velocity behind the detached bow wave. It is necessary to have a high Reynolds number, based on entrance diameter, so that the boundary layer does not fill the interior of the probe. If the boundary layer approaches the duct radius the conduction to the shield will be felt by the sensor.

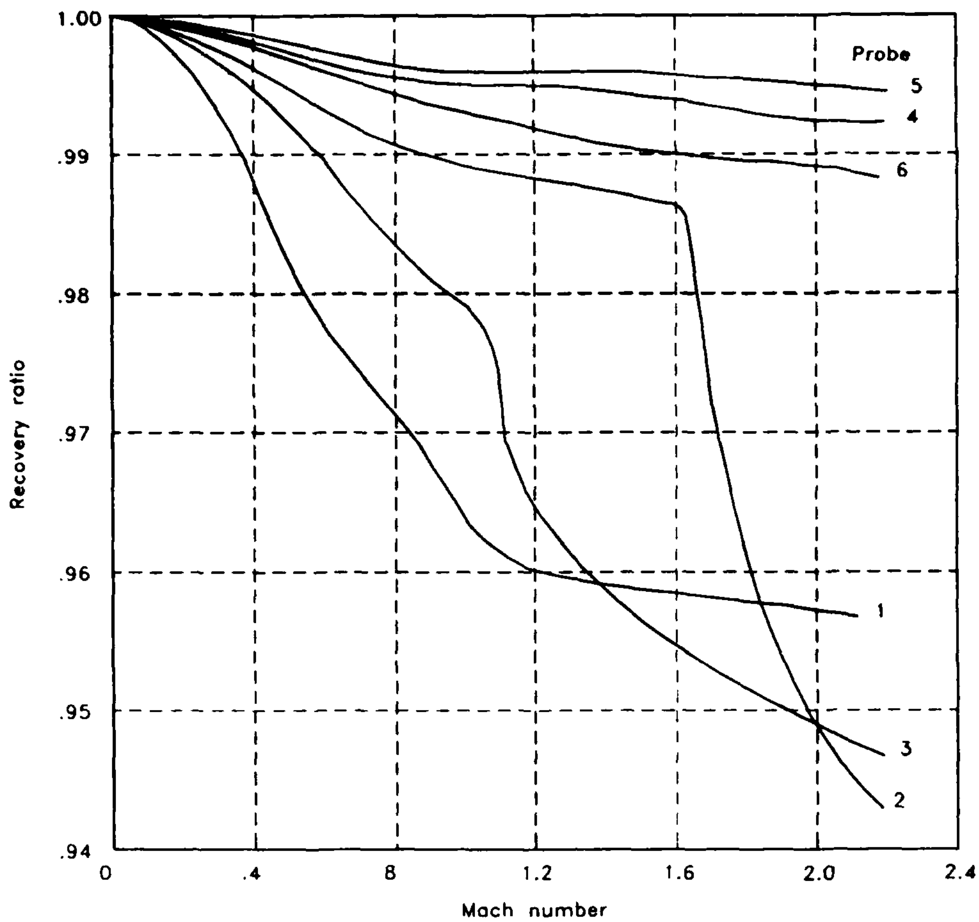


Figure 5: *Thermocouple calibration factors from Stickney [5].*

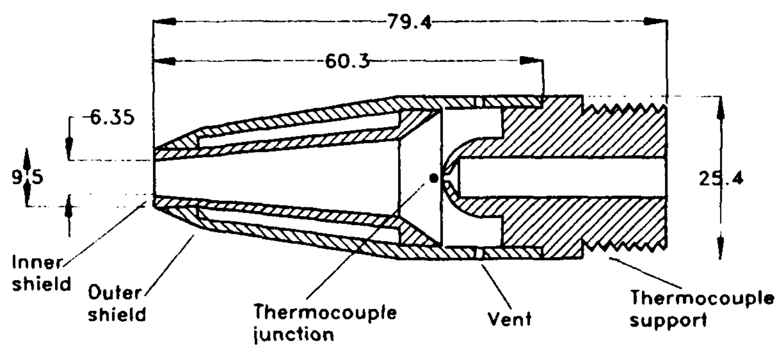


Figure 6: *Probe from Goldstein and Scherrer [6].*

Goldstein and Scherrer listed two problems in a shielded probe: 1) getting a fluid sample to the thermocouple with the minimum heat loss through the shield, and 2) arranging the thermocouple sensor in the probe so that it will receive the maximum amount of heat from the sample and loose the minimum amount of heat through radiation and conduction.

The total temperature during the tests was approximately 15.6°C and the Mach number was varied between 1.2 and 2.1. The calibration factor was found to be 0.992 over the Mach number range 1.36 to 2.01. The optimum ratio of vent area to entrance area was between 0.5 and 0.625 for a Mach number of 1.5.

A range of probes were tested in subsonic flows by Glawe, Simmons and Stickney [7]. All sensors were chromel-alumel thermocouples. Nine types of probe were tested. Probe 1 is illustrated in figure 7(a). Probe 2 will not be considered here. Probes 3 to 6 were similar to probes tested by Stickney [5]:-

Probe 3 similar to Stickney probe 4, figure 4(c)
Probe 4 similar to Stickney probe 1, figure 4(a)
Probe 5 similar to Stickney probe 3, figure 4(b)
Probe 6 similar to Stickney probe 6, figure 4(e)

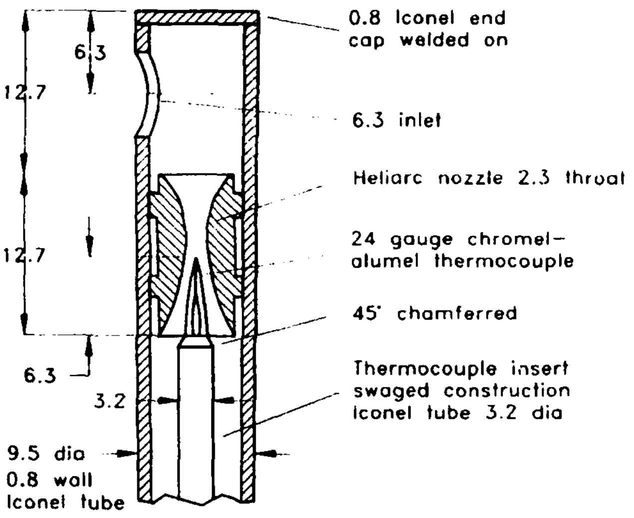


Figure 7(a): Probe 1 from Glawe, Simmons and Stickney [7].

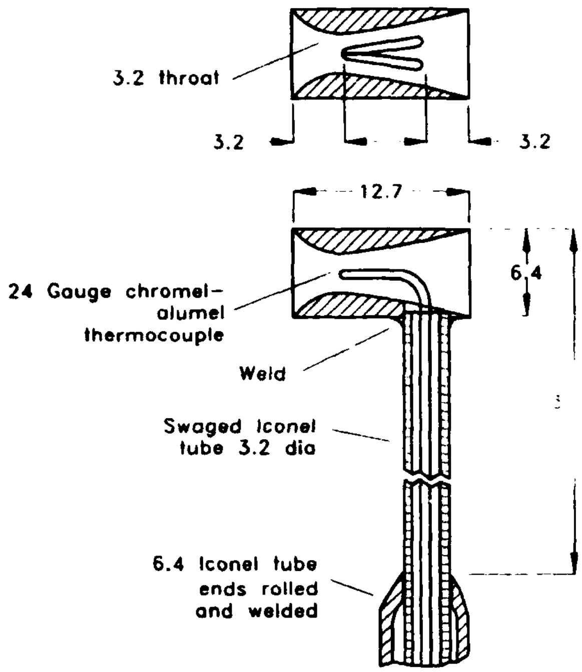


Figure 7(b): Probe 7 from Glawe, Simmons and Stickney [7].

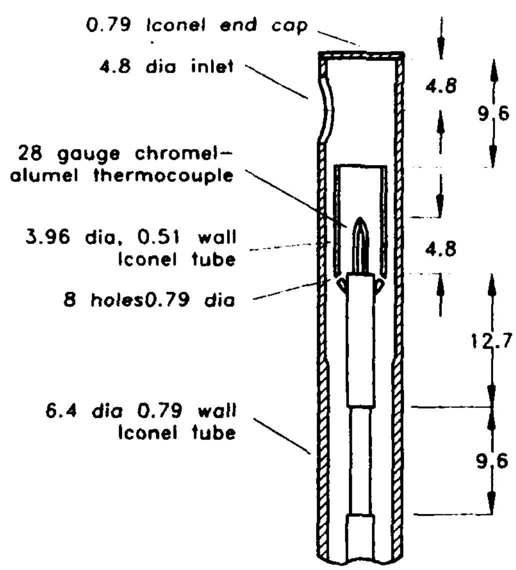


Figure 7(c): Probe 8 from Glawe, Simmons and Stickney [7].

Probes 7 and 8 are illustrated in figures 7(b) and 7(c). Probe 9 was similar to probe 8, but it was slightly larger. Probes 1, 8, and 9 were aspirated, and it was found that a constant indicated temperature of probe 9 was obtained when the pressure across the probe was greater than 100 mm of Hg.

Temperature and time constant data were obtained at static pressures 2/3 to 4/3 atmospheres, temperatures 833 to 1389°K, and Mach numbers 0.3 to 0.9. Recovery factors, defined by $\Delta = (Tt - Tg)/Tt$, were obtained for Mach numbers from 0.2 to 0.9 and static pressures from 1/7 to 4/3 atmospheres and at room temperature.

True total temperatures were assumed by Glawe, Simmons and Stickney [7] to be given by probe 1, and the deviation of the temperatures given by the other probes from the true total temperature were derived from comparisons with probe 1. Temperature deviations at a Mach number of 0.3 are given in figure 8. Probes 1,8 and 9 showed no variation of recovery factor with Mach number over the range 0.2 to 0.9, but all the other probes showed considerable variation.

The transient response for probes 8 and 9 strongly deviated from a first order system. The temperature initially rose at a high rate but the rate dropped as the final temperature was approached. It was suggested that the later part of the response was due to the slower heating of the shields which are of considerably greater mass than the thermocouple.

Glawe, Simmons and Stickney[7] derived an expression for the radiation correction (including a conduction correction) and for the time constant.

Design details and test results were given for two types of total temperature probes for hypersonic boundary layer measurements were given by Albertson and Bauserman[8]. The boundary layer to be studied was approximately 25 mm thick, so a small probe was needed. Their probe B is illustrated in figure 9. Probe A was similar to B with a support sleeve around the outside. The outside diameter of A was 2.4 mm and B was 1.5 mm. To reduce vertical averaging the entrance to the probes was flattened, probe A was 0.75 mm high and probe B was 0.5 mm high. The thermocouple was platinum-13%- rhodium vs platinum (type R), wire diameter 0.25 mm. A single platinum-20%-rhodium shield 0.125 mm thick was used in both cases, the main difference was the vent to entrance area: A 50% and B 60%. Estimated Reynolds number in the probe ranged from 63 to 2470.

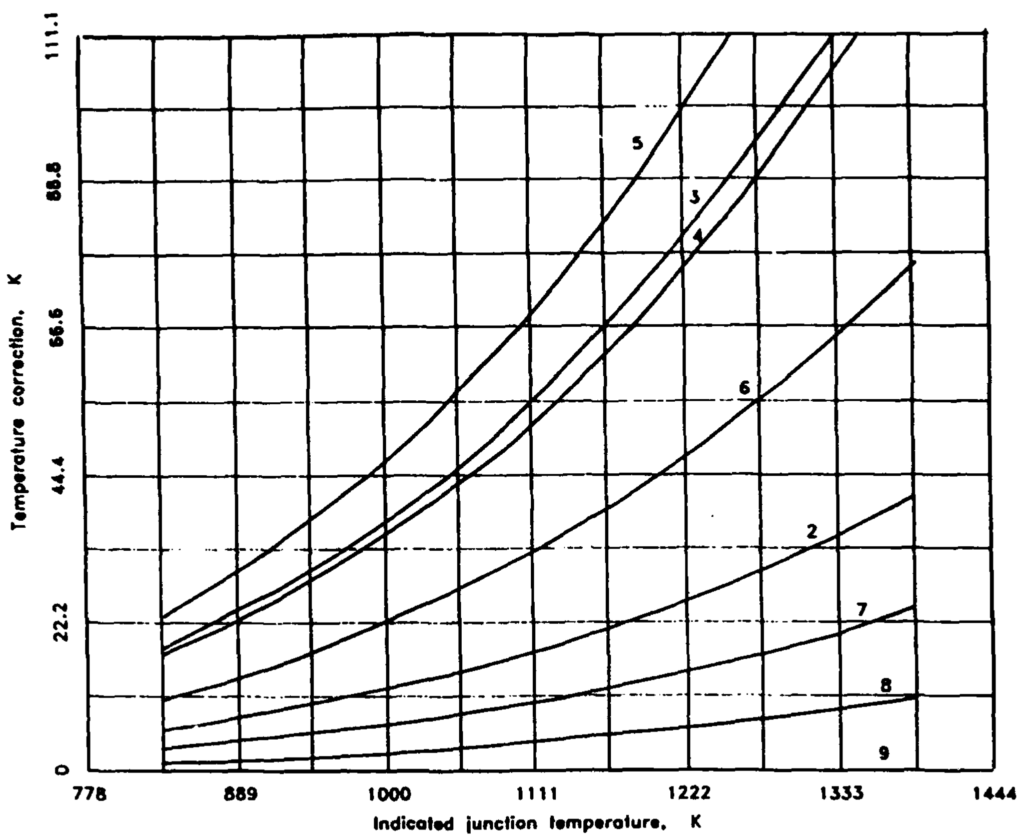


Figure 8: Temperature corrections at Mach number 0.3 for probes Glawe, Simmons and Stickney [7]

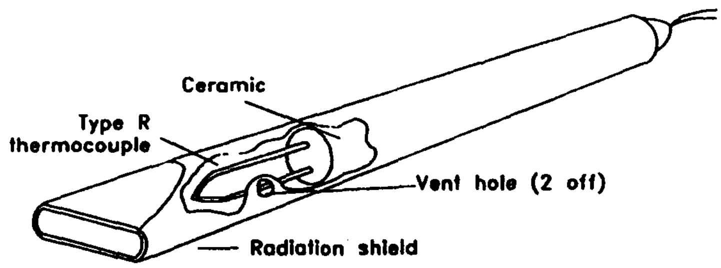


Figure 9: Albertson and Bauserman probe B [8].

The tests were carried out at the boundary layer edge where the Mach numbers were 5 and 6.2 and near the wall where the Mach number was 1.7. The pressures were equivalent to altitudes from 80,000 to 126,000 ft and the nominal stream temperatures were 1444 K and 1777 K.

Albertson and Bauserman[8] used a suggestion by Winkler[9] that the calibration factor K is proportional to Nusselt number given by:-

$$N_u = h_p d_w / k_w$$

where h_p is the convective heat transfer coefficient to the junction, d_w is the junction wire diameter, and k_w is the conductivity of the wire. Winkler also suggested a correlation of K with $p_t T_j^{-1.75}$, where p_t is the total pressure in the probe. (They plotted the relation but there was a large amount of scatter, and the relation was not convincingly established in this case.)

Albertson and Bauserman[8] derived a conduction correction, and more details of it will be given in Section 4.2 because it is the basis for the corrections developed in the present work. The conduction correction is a function of length/diameter of the thermocouple wires, the thermophysical properties of the wires, convective heat transfer to the wires and the probe support temperature.

They also calculated a radiation correction, which is a function of the emmitance of the thermocouple, the shield, the radiation view factor between the shield and the wires, and the temperature of the radiation shield.

A water cooled probe for supersonic flows was developed by Lagen and Seiner [10], and it is illustrated in figure 10. The probe was made from AISI Type 347 stainless steel, and it was water cooled and mounted on a water cooled wing to increase the temperatures the probe could sustain. The mass flow rate of coolant in the probe was 0.0295 kg/s. The thermocouples were type K chromel-alumel.

Total temperature measurements were made for flow from a 89.9 mm diameter nozzle with a Mach number of 2 and temperatures up to 1366K.

The surface temperature of the probe in operation was measured with a high resolution infrared system. The emissivity of the probe surface was found to be 0.80.

Probes were placed in the flow for tests of duration of 10 seconds with both the probe and wing with coolant circulating and not. Plots of measured temperature vs total temperature are given in figure 11. Radiation and conduction factors calculated, and the corrected results are also plotted in figure 11. The cooled probes reached steady state in 7-10 seconds, but separate tests showed that the uncooled probes took up to 2 minutes to reach steady state.

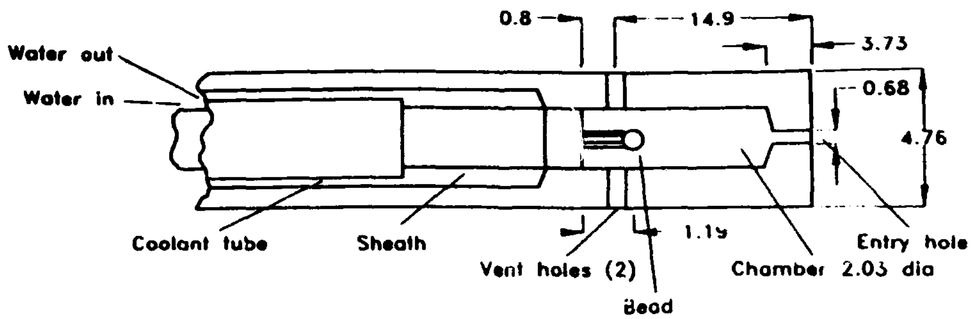


Figure 10: Probe from Lagen and Seiner [10].

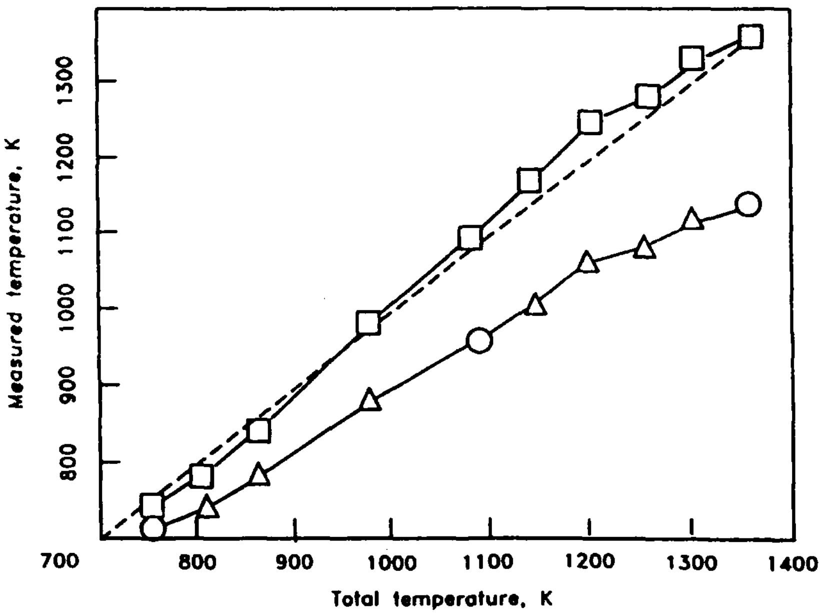


Figure 11: Measured or calculated temperature versus true total temperature from Lagen and Seiner[10]. 0 - Calibration points, Δ - measured bead temperature, [] - calculated temperature, ----- ideal calculated temperature.

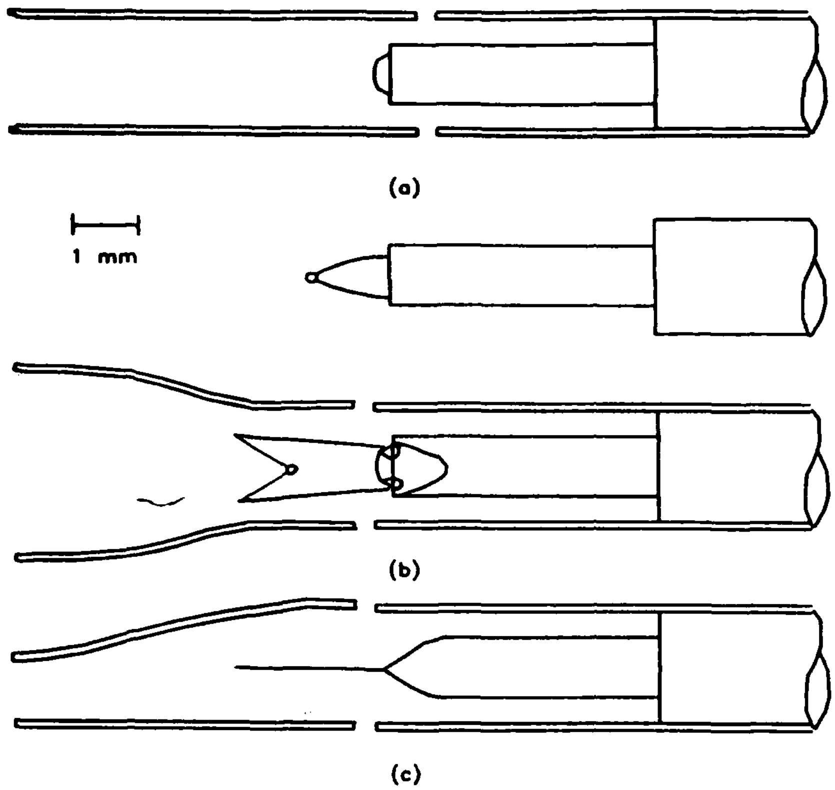


Figure 12: Bartlett, Edwards and Hillier [11] probes.

A total temperature probe for a gun tunnel was developed by Bartlett, Edwards and Hillier [11]. A schematic of the probe is given in figure 12. The basic design is a fine thermocouple stretched between 2 support prongs. Total temperature measurements were made in a hypersonic boundary layer with run times of order 3-4 ms. They quote a formula for correction including compressibility effects assuming no loss to surroundings. The calculated corrections were considered too idealised and experimental calibration was required.

The free stream conditions were To = 1064°K, $M_\infty = 9.26$, $Re_\infty = 5.5 \times 10^7$.

The first probe is illustrated in figure (12a), but the recovery factor was too low. It was improved by increasing the L/D and moving the bead away from the surface of the insulated support, see figure (12b). This produced a great improvement, but the best design was found to be figure (12c), where the L/D ratio of the thermocouple was 180/1. The entrance was flattened to improve resolution in the vertical direction.

Moeller, Noland and Rhodes [12] describe a number of probes developed at or for NASA and NACA. A design for a thermocouple to operate at >3250 K, see figure 13, resulted from a contract. It consisted of a W sheath and a coaxial W-26Re centre conductor. The sheath was formed by a thermochemical process. A

mandrel was made from mild steel and the W-26Re wire was placed in the centre longitudinal hole and crimped at the end. The assembly was placed in a quartz tube and heated by induction. Vaporised tungsten hexafluoride was introduced as the mandrel was rotated. When the coating was thick enough the assembly was placed in hot concentrated hydrochloric acid to dissolve the mandrel. However use of this probe was restricted because it was susceptible to stress fatigue.

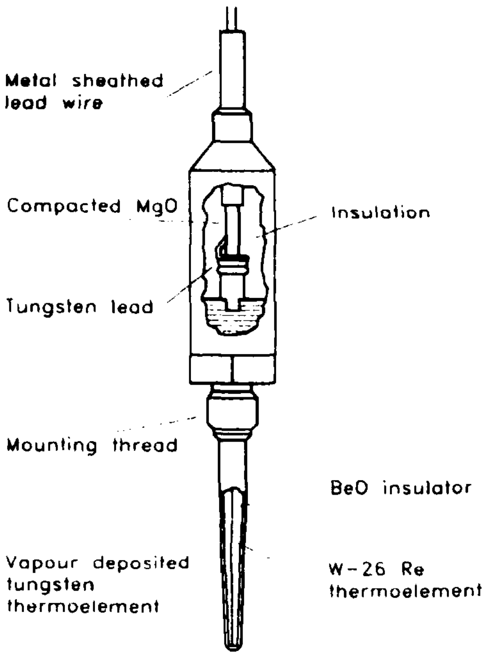


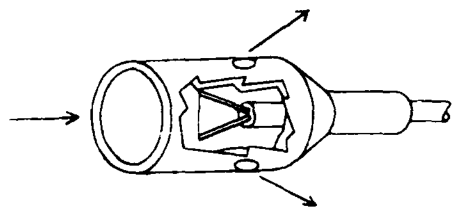
Figure 13: Probe from Moeller, Noland and Rhodes [12].

No high temperature sealing materials were available, so the thermocouple wires were brought out to a low temperature region where conventional materials could be used. Compensated lead wires were tested, but they introduced errors unless they were used at temperatures less than about 370°K.

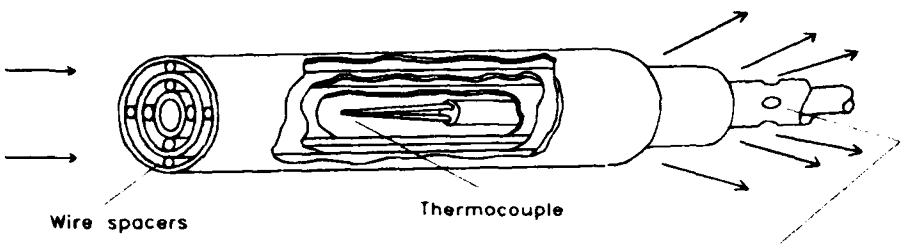
Preheating the thermocouples to near the expected test temperature was found to decrease the response time.

Two types of shielded thermocouples, see figure 14, were used in a wind tunnel with total temperature of 1820°K and a static pressure range from 15 to 120 microns of Hg. The thermocouples and shields were made from Pt-10Rh/Pt. The cold shield probe minimised conduction losses by using small diameter wires supported on V shaped thicker thermocouple wires. The shield had sufficient mass not to heat up during the run, so radiation corrections could be calculated with fixed boundary conditions. A probe with 3 radiation shields is shown in figure 14.

A fast response probe for measuring temperatures up to 1760°K for 10 seconds in gases with velocities up to 240 m/s and pressures of 5.6 MPa is illustrated in figure 15. The time constant was 0.1 second. A low thermal conductivity alloy was used for the mounting stem to reduce heat loss to the walls. Pt-10Rh thermocouples were used because W/W-Re thermocouples were too brittle and the tungsten was too hard to fabricate.



(a)



(b)

***Figure 14**: Two radiation shielded thermocouple probes from Moeller, Noland and Rhodes [12].*

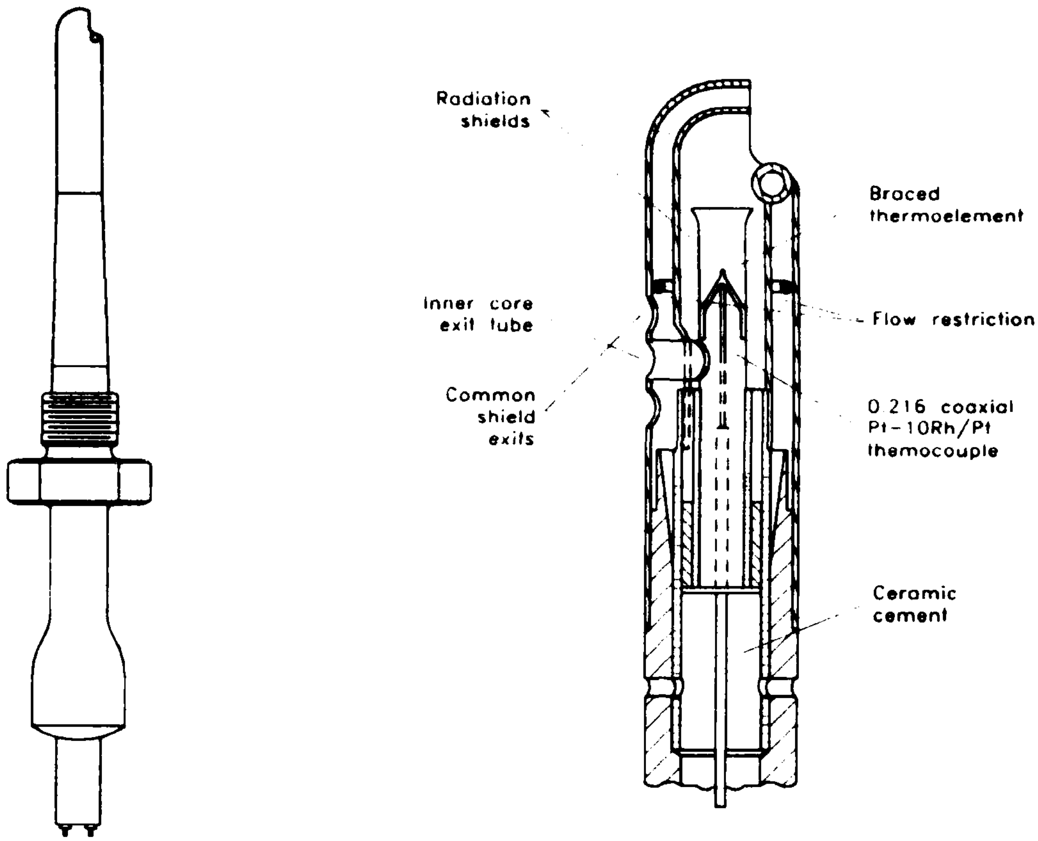


Figure 15: A fast responding shielded probe from Moeller, Noland, and Rhodes[15].

2.3 Probe materials

Moeller, Noland and Rhodes[12] reviewed the experience in NASA in temperature measurement in areas such as cryogenic temperatures, high temperatures, gas temperatures, surface temperature and instrumentation techniques. Some of the points of interest here are summarised below.

The noble metal alloy platinum-rhodium(Pt-Rh) thermocouples cannot be used much above 1920°K, and iridium-rhenium/iridium(Ir-Rh/Ir) thermocouples are limited to temperatures below 2420°K. Tungsten-Rhenium thermocouples, either W/W-26Re or W-5/W-26Re, can be used up to 3255°K but the W-5/W-26Re is preferred because it is less brittle. These thermocouples have high emf, chemical stability at high temperatures in vacuum and inert atmospheres, and relatively low vapour pressures.

Tables of physical and thermoelectric properties of high temperature thermocouple materials are given by Caldwell [13]. The use of refractory metals for ultra high temperature thermocouples is discussed by Lachman and McGurty [14]. In particular, data on W/Re and W/Mo thermocouples are given. W/Mo thermocouples have the disadvantage that the emf vs

temperature curves have a minimum value near 1000 K and the thermal emf is low.

There are a number of high temperature insulation materials that can be used in probes. Moeller, Noland, and Rhodes [12] consider beryllia (BeO) melting at 2820°K, and magnesia (MgO) melting at 3070°K. The electrical resistance falls dramatically with increasing temperature. In a particular geometry the resistance in a magnesia probe fell from 10^6 ohms at 1000°K to 200 ohms at 2200°K. Molybdenum reacted with BeO at 2600°K, but tungsten did not. At about 2700°K tungsten, tantalum, and W-26Re wires react slightly with BeO.

3. *Thermocouple Probe Design Considerations*

Moffat [3] stated that " the design of a probe for a given accuracy is, in reality, the design of a device to provide an environment inside the probe which will allow a bare wire junction to measure gas temperature with acceptable accuracy".

The two main sources of error in the measurement of total temperature are conduction and radiation from the thermocouple. As well as conduction of heat from the junction to the probe support base, Moffat stated that the shield and support parallel to the flow have a recovery factor of 0.86, the same as a bare junction exposed to the stream. This depression of temperature below the gas total temperature provides an additional driving force for conduction and radiation loss from the junction.

The conduction error can be reduced by [3]:

1. Decreasing the difference in temperature between the junction and the mount.
2. Increasing the junction length.
3. Decreasing the wire diameter or thermal conductivity.
4. Increasing the heat transfer coefficient h_c.

Only the junction length can easily be changed. The heat transfer coefficient can be increased by increasing the internal gas velocity in the probe, but this can only be carried so far before the flow can no longer be considered stagnant.

The radiation error can be reduced by [3]:

1. Decreasing emissivity.
2. Increasing h_c.
3. Increasing the wall temperature.

The emissivity can be decreased by coating the junction with a material like platinum, but contamination can increase the emissivity. h_c can be increased above the value obtained from the free stream pressure alone by aspirating the

probe using an external pump[3]. The wall temperature can be increased by using multiple shields.

From the literature reviewed above, it is apparent that bare wire thermocouples are suitable only for low temperature, subsonic flows. Single shields have been used, but at high temperatures the radiation losses would be too high or calculated correction factors uncertain. The multiple shield type of figure 14 would be an improvement, but the shields would only equilibrate to the recovery temperature and not the total temperature, and at high temperatures this difference could be significant. The aspirated probes appeared to give acceptable performance, but the difficulty of providing aspiration rules them out for the present purpose. The side entrance multishield probe in figure 15 appeared to be the best of the probes surveyed, but it would be too difficult to manufacture from tungsten, which would be required at the temperatures in rocket exhausts.

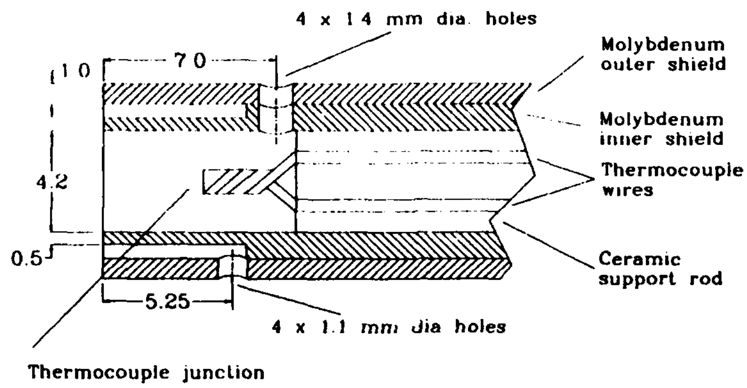


Figure 16: *Schematic of probe developed for this work.*

The final design chosen combined the requirements of multiple shields, sturdiness and practicality of manufacture. The probe is illustrated in figure 16. It consists of a twisted wire W-5%Re/w-26%Re thermocouple supported by a twin bore alumina rod. The thermocouple wire diameter is 0.5 mm and the shield material was tungsten.

For the purposes of calculating the conduction from the probe it would have been preferable to have used longer, straight rather than twisted, thermocouple wires in the probe. However, there was concern about the strength of that configuration and it was decided to use the twisted wires. Subsequent experience has indicated that straight wires may have been adequate.

The inner shield is vented with 4 holes with a total area of one half the inner shield entrance area. The space between the shields forms a second chamber which is vented through 4 holes with an area of half the entrance. The gas in the second chamber is slowed and heated to near the temperature of the inner

chamber. Observation of the inner shield through an outer vent hole during a test confirmed that the inner shield heated to incandescence very quickly, confirming that the shield was at a temperature high enough to minimise radiation losses from the thermocouple junction.

There was concern that the alumina support rod would not provide sufficient electrical insulation under measurement conditions. Two unconnected thermocouple wires were inserted in a rod and the rod heated under an oxy-acetylene flame for 2 minutes. The electrical resistance between the wires did not drop below 8 megohms, so the performance of the alumina was taken to be satisfactory.

4. Conduction and Radiation Corrections

4.1 General

The temperature indicated by a probe results from a heat flow balance

$$Q_c + Q_r + Q_k + Q_s = 0,$$

where

- Q_c is the rate of heat convection between gas and sensor
- Q_r is the rate of radiant heat exchange between the sensor and surroundings.
- Q_k is the rate of conduction of heat from the sensor by the thermocouple wire.
- Q_s is the rate of heat storage in the sensor.

The heat convection is given by

$$Q_c \sim h_c (T_g - T_w),$$

where h_c is the convective heat transfer coefficient, T_g and T_w are the gas and junction temperatures.

Moffat [3] stated that convection of heat to the thermocouple from the gas stream flowing over a solid surface is affected by the boundary layer which becomes established and it prevents the free stream from coming in contact with the surface. The thermal conductivity of the boundary layer determines the rate of transfer of heat from the free stream to the surface. This conductance is described by the heat transfer coefficient h_c, which is a function of Reynolds number Re, fluid properties, geometry and stream turbulence. The Nusselt number is defined as $Nu = h_c d / k_f$, where k_f is the thermal conductivity of the fluid. The Prandtl number is defined as $c_p\mu/k_f$, and was taken to be equal to 0.7. Moffat [3] presented the following empirical relationships between Nu and Re for Re in the range 100 to 10000.

Wire normal to flow: $Nu = (0.44 \pm 0.06)\ Re^{0.5}$

Wire parallel to flow: $Nu = (0.085 \pm 0.009)\ Re^{0.674}$

The data for these empirical relationships were obtained at relatively low turbulence levels, and rocket motors would have higher turbulence and hence higher Nusselt numbers. However, use of the empirical relationships would lead to a conservative probe design, and this was considered to be acceptable in the present case.

The radiative heat transfer is given by

$$Q_r \sim \sigma \varepsilon_w (T_d^4 - T_w^4)$$

where σ is the Stefan-Boltzmann constant, ε_w is the emissivity of the wire and T_d is the wall temperature. With the probe design considered here, it was considered that a radiation correction would be too difficult to develop, and since the probe was designed to minimise radiation losses, a radiation correction was not considered. The neglect of a radiation correction would increase the uncertainty of the results by an unknown, but probably not significant, amount.

Heat storage is given by

$$Q_s \sim \rho_w c_w \partial T_w / \partial t$$

where ρ_w is the density of the wire and c_w is the specific heat of the wire. Under steady state conditions heat storage effects would be zero, and non-steady effects will not be considered here.

Heat conduction will be discussed fully in the next section.

4.2 Calculation of the Conduction Correction

The calculation of the conduction correction is based on the method described by Albertson and Bauserman [8]. Flow within the probe is considered to be isentropic. The entry region flow is modelled as a divergent nozzle, with no heat loss in the recirculating flow behind the expansion. The aft end is modelled as a convergent nozzle with an exit area equal the sum of the areas of the vent holes. The flow is calculated assuming that the static pressure in the vent is equal to the external stream pressure. An equivalent assumption that the velocity through the vent holes may be taken as equal to the free stream velocity if the axis of the tube is parallel to the main stream and there are no obstructions outside the holes was suggested by Moffat [3].

The thermocouple in the probe will be modelled by the idealised geometry illustrated in figure 17.

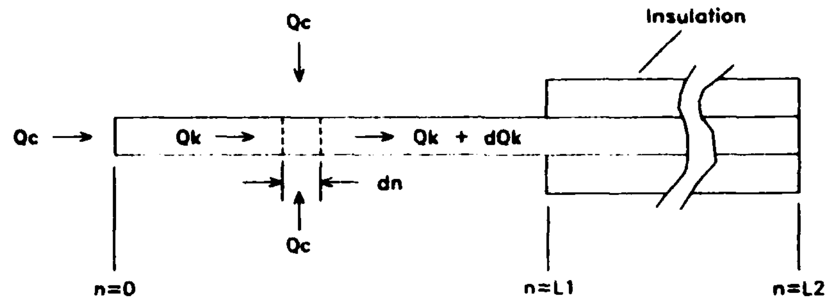


Figure 17: Schematic of probe for the conduction correction.

The quantities required to evaluate the correction are:-

h_p	heat transfer coefficient to the thermocouple
c_p	specific heat of the gases flowing over the probe
k_w	thermal conductivity of the thermocouple wire
k_p	thermal conductivity of the gas in the probe
A	area of the thermocouple wire = 1.964×10^{-7} m^2
d_w	diameter of the thermocouple wire = 0.5×10^{-3} m.
ρ	gas density
U	gas velocity
L	length of thermocouple wire diameter
μ	gas viscosity
γ	ratio of specific heats
R	gas constant
	relevant temperatures

and the dimensionless numbers

Bi	Biot number $\left(h_p d_w / 4k_w\right)^{\frac{1}{2}}$
N_u	Nusselt number $h_p d_w / k_p$
R_e	Reynolds number $\rho UL / \mu$
P_r	Prandtl number $\mu\, c_p / k_p$

The heat flow in a small segment of wire was assumed to be given by a one dimensional heat balance:-

$$h_p c_p\left[T_{aw} - T(n)\right] = -k_w A\left(\frac{d^2T}{dn^2}\right) \qquad (1)$$

where T_{aw} is the temperature of the wire if there is no heat loss to the environment. A general solution of the equation is

$$T(n) - T_{aw} = (T_j - T_{aw})\left\{\cosh\left[n\left(\frac{4h_p}{d_w k_w}\right)^{\frac{1}{2}}\right] + B_i \sinh\left[n\left(\frac{4h_p}{d_w k_w}\right)^{\frac{1}{2}}\right]\right\} \quad (2)$$

where Bi is the Biot number given by $(h_p d_w / 4k_w)^{\frac{1}{2}}$. If the temperature at n = L_1 was known the conduction correction $T_{aw} - T_j$ could be evaluated. Since this temperature was not measured, heat transfer from n = L_1 to n = L_2 was calculated by assuming one dimensional heat transfer with a temperature at L_2 of 27°C. With these assumptions the correction becomes

$$(T_{aw} - T_j) = \frac{T_{aw} - T(n = L_2)}{D_3} \quad (3)$$

where $$D_3 = D_4 + D_5(L_2 - L_1) \quad (4)$$

$$D_4 = \cosh\left[L_1\left(\frac{4h_p}{d_w k_w}\right)^{\frac{1}{2}}\right] + B_i \sinh\left[L_1\left(\frac{4h_p}{d_w k_w}\right)^{\frac{1}{2}}\right] \quad (5)$$

$$D_5 = \left(\frac{4h_p}{d_w k_w}\right)^{\frac{1}{2}}\left\{\sinh\left[L_1\left(\frac{4h_p}{d_w k_w}\right)^{\frac{1}{2}}\right] + B_i \cosh\left[L_1\left(\frac{4h_p}{d_w k_w}\right)^{\frac{1}{2}}\right]\right\} \quad (6)$$

For gas flow parallel to the thermocouple wires, Moffat [3] demonstrated a correlation between Nusselt number and Reynolds number as

$$N_u = 0.095 P_r^{0.31} R_e^{0.674} \quad (7)$$

The quantities h_p, c_p, k_w, ρ, k_p, and μ depend on the gas composition and temperature. The gas composition, c_p, gas molecular weight, and velocity U are obtained from the output of the REP code. Ideal gas behaviour is assumed, and the value of γ is obtained from c_p and R, the gas constant. The gas density ρ is calculated from the pressure using the ideal gas equation. The static pressure in the stream is assumed to be atmospheric. The convective heat transfer coefficient h_p is calculated from the Nusselt number.

The major gases in the plume are N_2, O_2, CO_2, H_2O, CO and HCl. Thermodynamic data for HCl was not readily available, and it was a relatively small component, so HCl was not included in calculations of gas properties. Data for CO was available only over a very limited range, and since it was a relatively small component, it too was not included. In view of the limited data available over the temperature range of interest, it was decided to approximate the gas as a mixture of air, H_2O and CO_2 with the appropriate composition. Literature values for viscosity of air were obtained for temperatures up to

1873°K, H_2O up to 773°K, and CO_2 up to 1325°K [15]. Literature values of thermal conductivity data for air and H_2O were obtained for the same temperatures, and for CO_2 to 819°K [15].

The viscosity and thermal conductivity data were fitted by a linear function over the temperature range of interest, extrapolating where necessary. The resulting functions are given below.

Gas	Viscosity (Pas)	Thermal conductivity (W/mK)
Air	$2.0\times10^{-5} + 2.25\times10^{-8}T$	$0.02 + 4.33\times10^{-5}T$
H_2O	$3.6\times10^{-8}T$	$-0.04 + 1.45\times10^{-4}T$
CO_2	$1.5\times10^{-5} + 2.4\times10^{-8}T$	$0.005 + 6.35\times10^{-5}T$

The thermal conductivity of the thermocouple was taken to be that of tungsten. The conductivity values obtained from Raznjevic[15] show a decrease with increasing temperature to a value of 98.9 $Wm^{-1}K^{-1}$ at 1273°K, and then a nearly linear increase to 146.5 $Wm^{-1}K^{-1}$ at 2673°K. However, Deshpande and Taylor[16] report the opposite trend at high temperatures, with the conductivity dropping from 116 W/mK at 1200°K to about 80$Wm^{-1}K^{-1}$ at 3000°K. The values of Raznjevic were chosen because these would give greater calculated corrections and reflect the greater uncertainty in the temperature value. The high temperature branch was approximated by

$$k_w = 55 + 3.5\times10^{-2}T \ Wm^{-1}K^{-1}$$

For a particular temperature in the probe the material parameters were evaluated and the Reynolds and Prandtl numbers were calculated. The Nusselt number was calculated from equation 7, and this value was used to calculate the convective heat transfer coefficient h_p. The Biot number and the factors D3, D4 and D5 were then calculated and used to evaluate the conduction correction from equation 3.

The method used to calculate the temperature and pressure in the probe depended on whether the stream was supersonic or subsonic. These two cases will be considered below.

Supersonic stream

When the external stream flow is supersonic there is a detached shock before the probe which can be considered to be a normal shock in front of the probe entrance. The flow variables at various locations will be identified by the following subscripts

1 Upstream of the shock
2 Downstream of the shock, outside the probe
3 Inside the probe

The total, or stagnation, temperature is the same on both sides of the shock, ie $T_{o1} = T_{o2} = T_{o3}$, where T_o is the total temperature. Since the probe is designed to measure T_{o1}, it will be assumed that this is known from the measured value of T_{o3}. The static temperature in region 1 is given by

$$T_1 = T_{o1} \Big/ \left(1 + \frac{\gamma - 1}{2} M_1^2\right) \tag{8}$$

where M_1 is the Mach number for the flow in region 1 given by

$$M_1 = U_1 \Big/ \sqrt{\gamma R T_1} \tag{9}$$

The static pressure upstream of the shock, P_1, is assumed to be standard atmospheric pressure, and the total pressure is given by

$$P_{o1} = P_1 \left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\frac{\gamma}{(\gamma - 1)}} \tag{10}$$

The static pressure downstream of the shock is given by

$$\frac{P_2}{P_1} = \frac{2\gamma}{\gamma + 1} M_1^2 - \frac{\gamma - 1}{\gamma + 1} \tag{11}$$

and P_{o2} is given by an equation similar to equation 10.

The downstream Mach number M_2 is given by

$$M_2^2 = \frac{M_1^2 + \dfrac{2}{\gamma - 1}}{\dfrac{2\gamma}{\gamma - 1} M_1^2 - 1} \tag{12}$$

In the probe the total pressure and total temperature are the same as the values downstream from the shock, ie $P_{o3} = P_{o2}$ and $T_{o3} = T_{o2}$. The values of the static variables P_3 and T_3 are calculated by equations similar to equations 8 and 10. These values are used to calculate the gas and thermocouple properties.

The Mach number in the probe is determined by the ratio of the probe internal area to the total area of the vents by the following equation

$$\frac{A_3}{A_v} = \frac{M_v}{M_3} \left[\frac{1 + (\gamma - 1) M_3^2 / 2}{1 + (\gamma - 1) M_v^2 / 2}\right]^{\frac{\gamma + 1}{2(\gamma - 1)}} \tag{13}$$

where the subscript v refers to the conditions in the vent. The vent is relatively close to the entrance to the probe, so the flow past the vent will be similar to the

flow behind the shock, and hence $M_n = M_2$. The area ratio in the current case equals 2, so the Mach number in the probe, M_3, can be evaluated.

The velocity in the probe is given by

$$U_3 = M_3\sqrt{\gamma R T_3} \tag{14}$$

Once U_3 has been determined, the conduction correction can be calculated from equation 3. Since the flow in the probe is not stagnant, the corrected junction temperature is not the total temperature but the recovery temperature. A factor $(1-r)U_3^2/2c_p$ must be added to the measured temperature.

The corrections were calculated using a spreadsheet, and a typical output is illustrated in figure 18. P_1, U_1, gas composition, and other gas properties were obtained from REP output. T_1 had to be calculated iteratively since the value of M_1 was required in equation 8, and a value of T_1 was needed to calculate M_1 from equation 10. Trial values of T_1 were substituted into equations 8 and 9 until the correct value of T_{01} was obtained.

The values of the variables after the shock in region 2 were calculated directly. The value of M_3 in region 3 of the probe was obtained by trial and error by calculating the entrance/vent area ratio, and adjusting M_3 until the area ratio was the correct value. The calculation of the corrections was then straightforward.

Subsonic stream

In this case region 1 does not occur, and the variables in region 2 are calculated in the same way as the variables in region 1 in the supersonic stream case. The variables in region 3 in the probe are calculated in the same way as the variables in region 3 in the supersonic stream.

4.3 Accuracy of probe temperature measurements

It would be desirable to be able to estimate the accuracy of the temperatures measured by probes described here. However, it is not practical to provide such an estimate. The sources of deviation of the measured value from the true value have been analysed and shown to be complex. For the conduction correction the values of the physical properties were in some doubt, and there would be variability in the construction of the probe. The effect of these uncertainties on the magnitude of the correction cannot be calculated. Losses due to radiation are not known, but are minimised by the probe design.

The assumptions made in the development of the probe design have been clearly outlined, but it remains the case that the suitability and accuracy of the the probes will be a matter of judgement in each particular application.

5. Conclusion

A design for a thermocouple probe to measure solid rocket exhaust temperatures has been produced. A method of correcting for conduction losses in the probe has been derived. Both the probe design and the correction were based on information from a literature survey on high temperature measurement.

PROBE CALCULATIONS			**SUPERSONIC STREAM FLOW**		
			BOOST		9/11/93
		Location			
		Axial distance	3		
		Radial distance	0.098		

PARTICULAR FLOW VARIABLES

U1	935			
Ttotal	2056			
Cp	1501			
MW	28.45			
Gamma	1.2417602	***Trial stream temperature***	Tstream	1765
R	292.23199			

BEFORE SHOCK

Pressure		Temperature		Mach No	
P1	1.013E+05	T1	1765	M1	1.168
Po1	2.220E+05	To1	2056		

AFTER SHOCK

Pressure		Temperature		Mach No	
P2	1.423E+05	T2	1887	M2	0.860
Po2	2.209E+05	To2	2056	U2	712

IN PROBE

Pressure		Temperature		Mach No	
P3	2.086E+05	T3	2033	M3	0.3045
Po3	2.209E+05	To3	2056	U3	262

Expo	4.636	Density	Rho	0.351069
Area Ratio	2.000	(Adjust M3 to give correct area ratio)		

CALCULATIONS

H t coef	h	2003.308		Fac1	355.2815	L1*Fac1	1.421126
		D3	38.65015	D4	2.278219	D5	727.4385

VELOCITY CORRECTION	3
CONDUCTION CORRECTION	45
TOTAL ERROR	49

CORRECTED TOTAL TEMPERATURE	2105
CORRECTED STREAM TEMPERATURE	1807

VISCOSITY AND THERMAL CONDUCIVITY OF GAS IN PROBE

Gas	Level	Viscosity		Thermal conductivity				
Air	0.65	6.63E-05		0.109034				
H2O	0.22	7.4E-05		0.258151				
CO2	0.13	6.43E-05		0.13557				
DISTIN	UIN	TOIN	CPIN	MWIN	AIRIN	H2OIN	CO2IN	SUMIN
98	935	2056	1501	28.45	21.0	7.2	4.2	32.4

FLOW DEPENDENT VARIABLES

Viscosity in Probe	Mu	6.77E-05	
Thermal conductivity of fluid	Kf	0.145606	(Data from Raznjevic)
Thermal conducivity of wire	Kw	126.9675	(Data from Raznjevic)
Biot Number	Bi	0.04441	
Prandtl Number	Pr	0.698314	
Nusselt Number	Nu	6.879229	
Reynolds Number	Re	677.7951	

PROBE CONSTANTS

Diameter of wire	d	0.0005	Area of one wire	Aw	1.96E-07
Exposed length of TC	L1	4.00E-03	Exposed Area of TC	Aex	1.26E-05
Total length of TC	L2	5.40E-02	(2 wires)		
Gas constant	Rbar	8314			

Figure 18: *Spreadsheet output of calculation of conduction correction*

6. References

1. Blair, M.A. and Warren, R.C. "*Rocket plume temperature measurement*". MRL Technical Report in preparation.

2. Cambel, A.B. and Jennings (1958), B.H.,"*Gas Dynamics*", McGraw-Hill, New York, Chapter 12.

3. Moffatt, R.J. (1962) "*Gas measurement and control in science and industry*", Dahl, A.I. Ed, Reinhold, New York.

4. Scadron, M.D. and Warshawsky, I. (1952) "*Experimental determination of time constants and Nusselt numbers for bare wire thermocouples on high velocity air streams and analytic approximation of conduction and radiation errors*". NACA Technical Note 2599.

5. Stickney, T.M. (1955) "*Recovery and time response characteristics of six thermocouple probes in subsonic and supersonic flow*", NACA Technical Note 3455.

6. Goldstein, D.L. and Scherrer, R. (1949) "*Design and calibration of a total-temperature probe for use at supersonic speeds*". NACA Technical Note 1885.

7. Glawe, G.E., Simmons, F.S. and Stickney, T.M. (1956) "*Radiation and recovery corrections and time constants of several chromel-alumel thermocouple probes in high-temperature, high-velocity gas streams*". NACA Technical Note 3766.

8. Albertson, C.W. and Bauserman Jr, W.A. (1993) "*Total temperature probes for high-temperature hypersonic boundary-layer measurements*". NASA Technical Memorandum 4407.

9. Winkler, E.M. (1954) "*Stagnation temperature probes for use at high supersonic speeds and elevated temperatures*". NAVORD Rep 3834, US Navy.

10. Lagen, N.T. and Seiner, J.M. (1991) "*Correction analysis for a supersonic water cooled total temperature probe tested to 1370 K*". International Congress on Instrumentation in Aerospace Simulation Facilities, IEEE, New York, USA.

11. Bartlett, R.F., Edwards, A.J., and Hillier, R. (1979) "*Development and calibration of a total temperature probe for the Imperial College Aeronautics Department gun tunnel*". IC Areo Report 79-02.

12. Moeller, C.E., Noland, M. and Rhodes. B.L. (1968) "*NASA contributions to development of special-purpose thermocouples*". NASA SP-5050.

13. Caldwell, F.R. (1962) "*Thermocouple materials" in "Temperature its measurment and control in science and industry*", Dahl, A.I. Ed, Reinhold, New York, p81

14. Lachman, J.C. and McGurty, J.A. (1962) " *The use of refractory metals for ultra high temperature thermocouples.*" in "*Temperature its measurment and control in science and industry*", Dahl, A.I. Ed, Reinhold, New York, p177

15. Raznjevic, K. (1976) "*Handbook of Thermodynamic Tables and Charts*" Hemisphere, Washington.

16. Deshpande, M.S. and Taylor, R.E. (1983) "*Extending the capabilities of the multiproperties apparatus for thermophysical property determinations*". in "*Thermal conductivity 16*", Larsen, D.C. Ed, Plenum Press, New York.

REPORT NO.
DSTO-TR-0006

AR NO.
AR-008-651

REPORT SECURITY CLASSIFICATION
Unclassified

TITLE

Design of thermocouple probes for measurement of rocket exhaust plume temperatures

AUTHOR(S)
R.C. Warren

CORPORATE AUTHOR
DSTO Aeronautical and Maritime Research Laboratory
GPO Box 4331
Melbourne Victoria 3001

REPORT DATE
June 1994

TASK NO.
ADA 92/195

SPONSOR

FILE NO.
510/207/0090

REFERENCES
16

PAGES
40

CLASSIFICATION/LIMITATION REVIEW DATE

CLASSIFICATION/RELEASE AUTHORITY
Chief, Explosives Ordnance Division

SECONDARY DISTRIBUTION

Approved for public release

ANNOUNCEMENT

Announcement of this report is unlimited

KEYWORDS

Rocket Plume Temperature   Thermocouple   High Temperature

ABSTRACT

This paper summarises a literature survey on high temperature measurement and describes the design of probes used in plume measurements. There were no cases reported of measurements in extreme environments such as exist in solid rocket exhausts, but there were a number of thermocouple designs which had been used under less extreme conditions and which could be further developed.

Tungsten-rhenium(W-Rh) thermocouples had the combined properties of strength at high temperatures, high thermoelectric emf, and resistance to chemical attack. A shielded probe was required, both to protect the thermocouple junction, and to minimise radiative heat losses. After some experimentation, a twin shielded design made from molybdenum gave acceptable results. Corrections for thermal conduction losses were made based on a method obtained from the literature. Radiation losses were minimised with this probe design, and corrections for these losses were too complex and unreliable to be included.

Design of Thermocouple Probes for Measurement of Rocket Exhaust Plume Temperatures

R.C. Warren

(DSTO-TR-0006)

DISTRIBUTION LIST

Director, AMRL
Chief, Explosives Ordnance Division
Dr R.J. Spear
Mr R.C. Warren
AMRL Library - Maribyrnong

Chief Defence Scientist (for CDS, FASSP, ASSCM)	1 copy only
Director, ESRL	
AMRL Library - Fishermens Bend	
Head, Information Centre, Defence Intelligence Organisation	
OIC Technical Reports Centre, Defence Central Library	
Officer in Charge, Document Exchange Centre	8 copies
Air Force Scientific Adviser, Russell Offices	
Scientific Adviser - Policy and Command	
Senior Librarian, Main Library DSTOS	
Librarian, DSD, Kingston ACT	
Serials Section (M List), Deakin University Library, Deakin University, Geelong 3217	
NAPOC QWG Engineer NBCD c/- DENGRS-A, HQ Engineer Centre, Liverpool Military Area, NSW 2174	
ABCA, Russell Offices, Canberra ACT 2600	4 copies

Librarian, Australian Defence Force Academy
Head of Staff, British Defence Research and Supply Staff (Australia)
NASA Senior Scientific Representative in Australia
INSPEC: Acquisitions Section Institution of Electrical Engineers
Head Librarian, Australian Nuclear Science and Technology Organisation
Senior Librarian, Hargrave Library, Monash University
Library - Exchange Desk, National Institute of Standards and Technology, US
Acquisition Unit (DSC-EO/GO), British Library, Boston Spa, Wetherby, Yorkshire LS23 7BQ, England
Library, Chemical Abstracts Reference Service
Engineering Societies Library, US
Documents Librarian, The Center for Research Libraries, US
Army Scientific Adviser, Russell Offices - data sheet only
Navy Scientific Adviser - data sheet only
Director General Force Development (Land) - data sheet only
DASD, APW2-1-OA2, Anzac Park West, Canberra ACT - data sheet only
SO (Science), HQ 1 Division, Milpo, Enoggera, Qld 4057 - data sheet only
Librarian - AMRL Sydney - data sheet only
Counsellor, Defence Science, Embassy of Australia - data sheet only
Counsellor, Defence Science, Australian High Commission - data sheet only
Scientific Adviser to DSTC Malaysia, c/- Defence Adviser - data sheet only
Scientific Adviser to MRDC Thailand, c/- Defence Attache - data sheet only

Dr W.H. Jolley, EOD Salisbury
Mr M.A. Blair, EOD Salisbury
Mr D. Kilpin, EOD Salisbury
Mr A. Lee, EOD Salisbury
Dr J.G. Bain, AED
Dr S.M. Henbest, AED